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Research Article

Mechanical properties of thin roots of tree species for shallow landslide protection along an altitudinal gradient

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Abstract

Shallow landslides and erosional problems in mountain areas are a recurrent issue that can represent a threat to human life and impact landscape ecology in many ways. Soil bioengineering is an approach that uses biological and ecological knowledge and engineering design principles to restore shallow-landslide-affected slopes. Tree species can be used as elements of soil bioengineering to reduce erosion and provide reinforcement through their roots. For this reason, we estimated the mechanical properties of thin tree roots from three vegetation communities along an elevational gradient. Our results showed that *Piper amalago* and *Pinus teocote* consistently exhibited higher mechanical properties than all species analyzed. The absence of a consistent altitudinal trend suggests that local site conditions and species-specific traits have a stronger influence on root mechanics than elevation alone.

Key words: Elasticity, forest, root reinforcement, tensile strength, thorn scrub

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Introduction

Mountain environments are ecologically unique and play an important role in maintaining species biodiversity; however, they are also very susceptible when hydro-meteorological events occur. Rainfall-induced shallow landslides are a very important and dangerous hazard in mountainous areas. Shallow landslides are defined as the movement of soil along a slope with a sliding surface up to 2 m (Schaller et al. 2025). The investigation of the mechanical contribution of plant roots to soil has significant implications. From an environmental point of view, plant-based soil stabilization represents a solution for erosion control and ecosystem resilience, contributing to the restoration of degraded landscapes while maintaining soil health and plant species biodiversity. From a societal standpoint, the use of plants to reduce shallow landslides protects human lives and infrastructure, reducing economic losses in vulnerable rural mountainous regions.

Soil bioengineering is a nature-based solution that can be an alternative or complement to the conventional hydraulic or civil engineering approaches of

soil stabilization (Kettenhuber et al. 2022). Using biological and ecological knowledge and engineering design principles, this discipline allows plants to be used as living structures or in combination with plant community propagation to naturally control soil erosion, sediment flows, and flooding (Stokes et al. 2009; Bischetti et al. 2012; Jiang et al. 2024; Suresh et al. 2024). The development of natural vegetation on this structural intervention is of fundamental importance for soil erosion protection (Romano et al. 2022), especially on mountain slopes.

Tree species can help prevent soil erosion and shallow landslides in two ways: modifying the soil moisture regime via evapotranspiration and providing root reinforcement to soil (Stokes et al. 2009; Cao et al. 2025; Zhu et al. 2025). Soil root reinforcement is a very significant contribution by tree species to soil stability. If soils are shallow, roots can reach deeper to more stable substrates, and dense lateral root systems in upper soil horizons can form a mesh that stabilizes the soil. According to Wu et al. 1988, the root systems of trees can provide reinforcement in potential slope failures (Flepp et al. 2021; Huang et al. 2025; Kong et al. 2025). In mountainous areas, tree basal areas, organic matter, and dense root systems are of interest to prevent surface erosion problems (Schmidt et al. 2001; Hao et al. 2021; Gobinath et al. 2022; Liu et al. 2022).

The effect of roots on soil fixation has been studied and reported by many authors in many countries over the years (Genet et al. 2006; Abdi et al. 2018; Valizade and Tabarsa 2020; Masi et al. 2021; Meijer 2021; Su et al. 2021; Zhu et al. 2022). Models of root mechanical contribution to soil were created, usually overestimating the effect of roots on soil cohesion by assuming that during failure the roots break at the same time (Bischetti et al. 2009; Schwarz et al. 2013) or that roots are oriented perpendicular to the slip surface (Nghiem et al. 2003; Pollen and Simon 2005; Danjon et al. 2007). Quantifying the exact additional soil shear strength gained by the presence of roots is difficult to achieve.

For tree root systems, there must be a distinction between thin roots (<10 mm) and thick roots (>10 mm). When soil failure occurs, thin roots can act as flexible elements of a mesh to contain soil, and the thick roots of trees can act as structural pillars adding longitudinal strength (Reubens et al. 2007). Previous research efforts indicate that thin roots are significantly stronger than thick roots, mainly because of differences in cellulose content (Genet et al. 2005). Some thin roots showed tensile strength values over 700 MPa, surprisingly stronger than steel (Bischetti et al. 2005). Therefore, the thickness of roots and how flexible the roots can be is a very important factor to consider, as it can indicate their ability to penetrate soil and reinforce it against failures.

Soil characteristics vary widely across regions and are highly susceptible to rapid modification under anthropogenic disturbances and meteorological events. As a result, estimating root reinforcement potential while assuming that plant species behave similarly across different soil types can lead to significant underestimation or overestimation of their capacity as soil bioengineering agents.

Therefore, advancing this field requires the development of local databases documenting the mechanical properties of native plant species. Such information can subsequently be integrated with local soil characteristics and root area estimations from the sites to enable a more accurate assessment of their potential for use in soil bioengineering strategies aimed at stabilizing degraded mountainous regions.

Consequently, the main objective of this study is to estimate the mechanical properties—tensile strength and elasticity—of thin roots from tree species across three distinct vegetation communities distributed along an elevational gradient.

Methods

Study area

The study area is in the Natural Protected Area Altas Cumbres in Ciudad Victoria, Tamaulipas, Mexico. The altitude fluctuates between 350 m a.s.l. and 2180 m a.s.l. The highest elevation is found in the northwest, and the lowest elevation is in the eastern part of the area. The Natural Protected Area Altas Cumbres covers around 30,327.85 hectares and was declared in 1997 with the purpose of protecting and conserving the hydrological watershed, vegetation species, and biodiversity. The geomorphology of the area is characterized by secondary limestone formations folded into sharp anticlines and synclines. The mountain range is rugged and highly dissected along most of its length, with less pronounced escarpments toward the north. Slopes range from 0° to 58°, creating zones with high susceptibility to landslides. The rich biodiversity of both plant and animal species further highlights the ecological value of the region and underscores its importance for conservation. The climate is highly variable depending on altitude, with a prevailing humid subtropical climate (Cwa) according to the Köppen climate classification. The average monthly temperature ranges from 20 °C to 35 °C, with occasional extreme values of 10 °C in January and 48 °C in July. The study was performed in three sampling sites: 1) Tropical semi-deciduous forest (TSdF) located at 23°45.30'N, 99°18.39'W at an altitude of 340 m a.s.l.; 2) Tamaulipan Thornscrub (TTS) located at 23°46.32'N, 99°14.96'W at an altitude of 550 m a.s.l.; 3) Oak–Pine Forest (OPF) located at 23°46.62'N, 99°12.55'W at an altitude of 1100 m a.s.l. (Fig. 1).

Root sampling and processing

The tree specimens chosen were representative species of the area. The root system of the specimens was cleared from the soil. After the thin root area was completely exposed, it was examined for external damage, and segments of thin roots were collected for further analysis. The classification of roots in this study was defined based on Stokes's (2009) list of desirable plant root traits for protecting natural slopes, which follows the processes governing soil fixation and divides thin roots into three classes depending on diameter: fine roots (>0.0–2.0 mm), thin roots (>2.0–10.0 mm), and thick roots (>10.0 mm). For this study, because of variation in root diameter among species, we statistically separated three categories of roots: small-diameter roots, medium-diameter roots, and large-diameter roots, all belonging to the thin part of the tree root system (Fig. 2). The contribution of thin tree roots is especially useful because, according to Dupuy et al. (2005), this group contributes to enhanced soil fixation due to bending and branching patterns.

The tests were carried out using a digital dynamometer with a 500 N capacity (Baoshishan ZP) placed on a test stand consisting of a clamp system on each side (Fig. 3). Root samples were positioned and clamped carefully to the experimental device at both extremities, avoiding damage to the root samples.

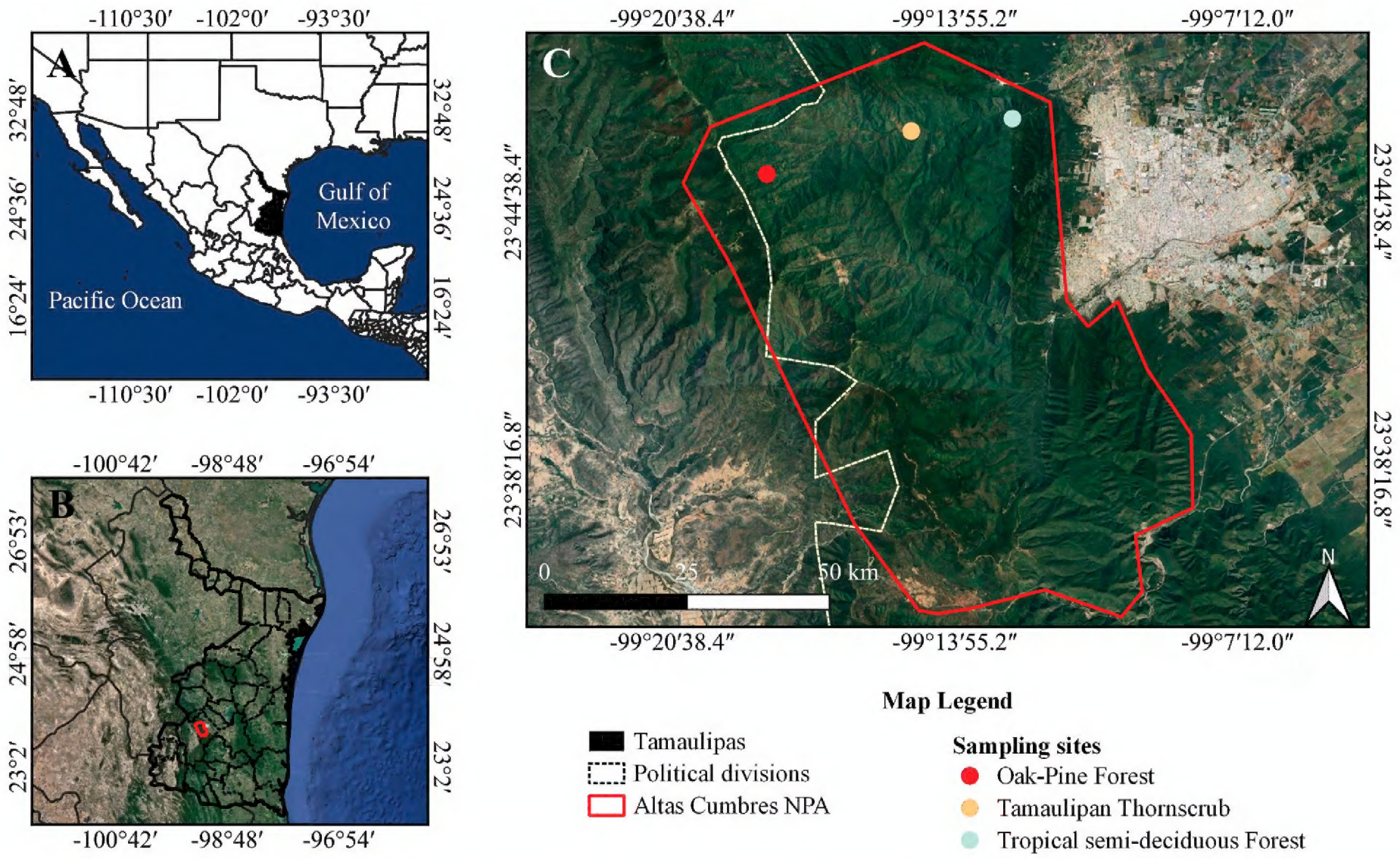

Figure 1. Study area and location of sampling sites. **A.** Location of Tamaulipas in Mexico; **B.** Location of the Natural Protected Area Altas Cumbres; **C.** Location of the sampling sites with different vegetation.

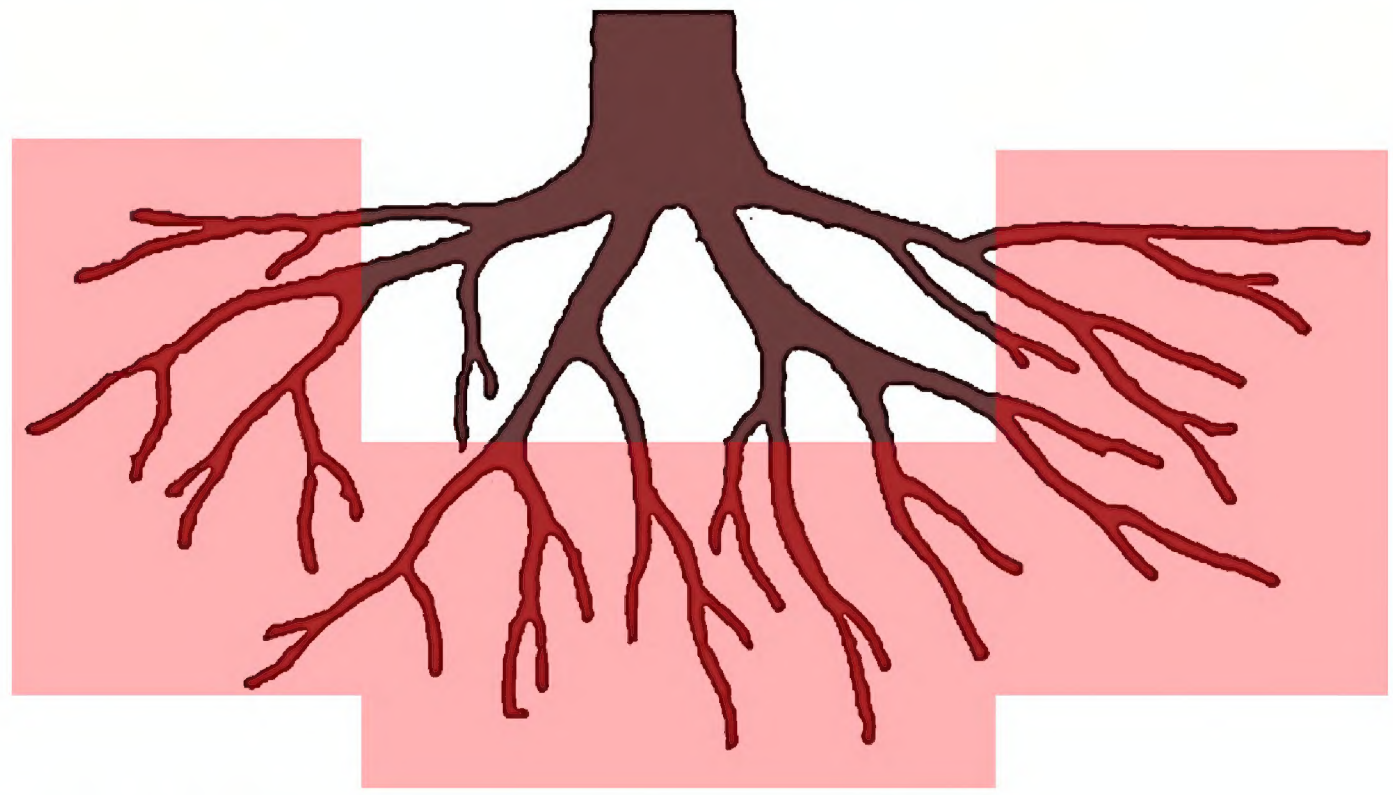

Figure 2. Diagram of the position of thin roots tested in this study.

The elastic properties of each root sample were determined using the following formula:

$$E = \frac{Ts/Cs}{L_1/L_0}$$

where Ts is the peak maximum force recorded by the dispositive, C_s is the cross-sectional area, L_1 is the change of length of root sample, and L_0 is the original length (Fu et al. 2024).

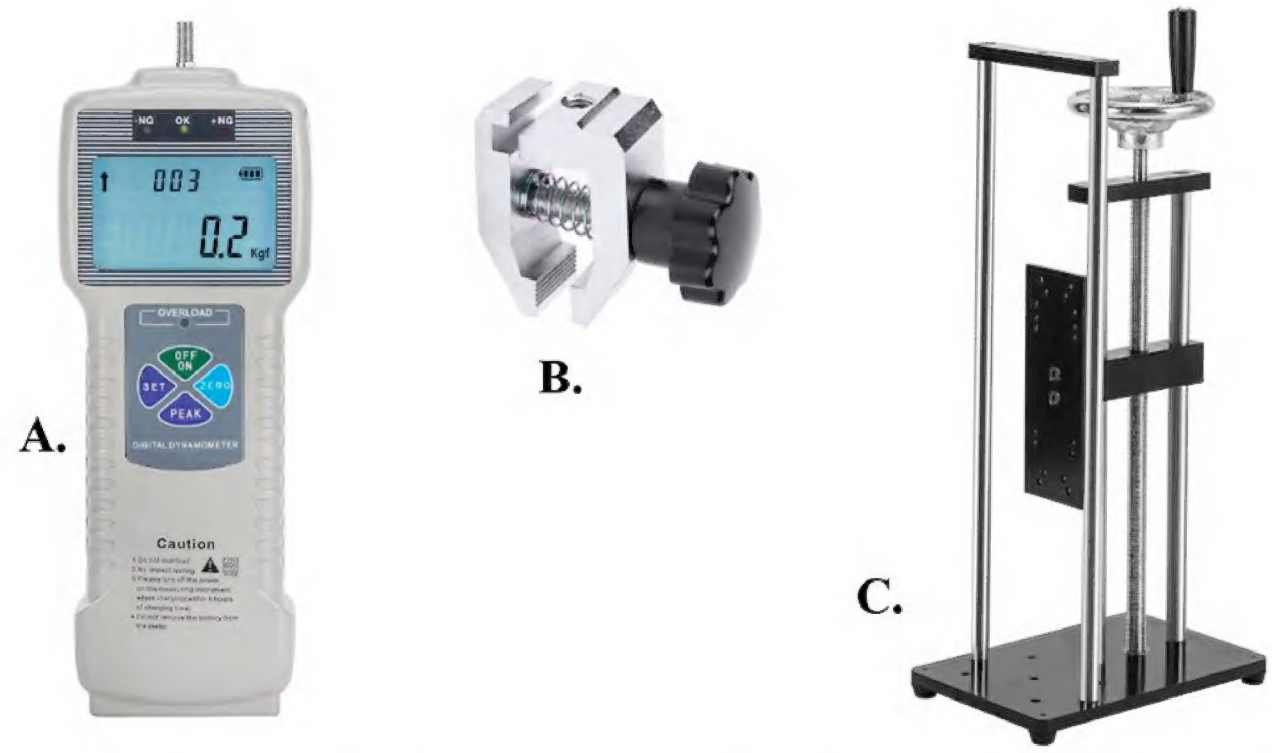

Figure 3. Device used for testing. **A.** Dynamometer; **B.** Clamp system; **C.** Test stand.

Diameters were measured with a digital caliper (Mitutoyo) at three different points (upper, middle, and lower) to calculate a mean diameter corresponding to the breaking point of the samples. A constant speed of 10 mm/min was maintained for each test, and the dynamometer recorded the maximum tensile strength at root breakage.

Tree species

The tree species selected were healthy and growing on the slopes of the study area. For the taxonomic identification of the specimens, the work of Stubbendieck et al. (2003) was consulted. Likewise, the botanical nomenclature was homogenized using the International Plant Name Index (International Plant Name Index 2023).

The description of the species found in the study sites is as follows:

Ficus cotinifolia Kunth (common name: amate) is a tree that can reach a height of 20 m, beginning as an epiphyte and becoming a strangler. Young branches are ribbed, floppy, and light gray. Leaves are obovate, ovate to elliptic, 5.5–13 cm long, and 3.5–6.5 cm broad. It is distributed in warm climates and is usually associated with disturbed vegetation of tropical deciduous forest (Ibarra-Manríquez 1992; Piedra-Malagon et al. 2006).

Annona globiflora Schltdl. (common name: anona) is a small tree of 1–4 m tall. Young branches, buds, and petioles are densely pubescent, with brownish trichomes that are appressed or slightly raised. Persistent leaves are 4–8 cm long and 1–3 cm wide, rounded at the base. It is frequent in tropical deciduous forests and can be found with flowers and some fruits from April to August and only with fruits toward the end of the year (Ortiz-Rodriguez et al. 2015).

Taxodium mucronatum Ten. (common name: ahuehuete) is a majestic-looking tree that reaches up to 40 m in height. It has light brown bark, straight leaves 8–200 mm long, and inflorescences 15–30 cm long. It is a species of riparian habitats with large water requirements, located in permanent or semi-permanent streams and occasionally in places without direct water contact but with a shallow groundwater table (Martínez-Sifuentes et al. 2021).

Sommera grandis Standl. (common name: palo colorado) is a tree that reaches a height of 8 m, with reddish-brown branches. Leaves have thick petioles of 0.8–2.5 cm, are light green and pale on the underside, and have subsessile flowers or a fruiting pedicel 3–8 mm long (Borhidi and Stranczinger 2012).

Piper amalago L. (common name: cordoncillo o higuillo de limón) is a small tree or shrub 1–6 m tall, profusely branched. Stems are green, internodes 3.5–5.5 cm long, and leaves are uniform in shape and size along all axes, symmetrical, and immensely ovate. It lives in warm, semi-warm, and temperate climates. It is a wild plant that grows along roads and is associated with disturbed vegetation of deciduous, subdeciduous, and evergreen tropical forests (Santos et al. 2015).

Randia obcordata S. Watson (common name: altanisa) is a small tree or shrub that grows primarily in the seasonally dry tropical biome. It is very dominant in Tamaulipan thornscrub, reaching heights of around 3 m (Villaseñor 2016).

Celtis laevigata Willd. (common name: palo blanco) is a medium-sized tree with narrow and jagged leaves. It grows in mountain zones, and the leaves contain chemicals that inhibit the germination of other plant species (Midolo 2024).

Zanthoxylum fagara L. Sarg. (common name: limoncillo) is a tree belonging to the family Rutaceae. It reaches up to 30 m in height. Its trunk is covered by abundant, very strong conical spines. Leaves are spirally arranged and have 3–7 leaflets. It inhabits regions from Mexico to Central America (Valdes-Alameda et al. 2020)

Karwinskia humboldtiana Schult. Zucc. (common name: tullidora) is a shrub or small tree 1–8 m tall, with a trunk that can measure 20 cm in diameter. Leaves are small (1–1.5 mm long), glossy green, paler below, with black spots on the main veins, opposite, and with linear stipules. It is found in various habitats, from deciduous tropical forest and dry scrub to oak forest and grasslands, between 250 and 2200 m a.s.l. (Fernandez-Nava 1996).

Quercus rysophylla Weath. (common name: encino colorado) is an evergreen tree of rapid growth that can reach 25 m in height. Leaves are alternate, simple, rigid, and elliptic, 7–25 cm long and 2–8 cm wide. Acorns are ovoid, mucronate, and glabrous at maturity, 1–1.7 cm long, single or in pairs, and sessile. The cupola, golden-colored and silky when young, occupies one-third of the acorn and matures after 2 years. This species is endemic to Mexico and found mostly at mid-altitudes in the Sierra Madre Oriental (Sanchez-Castillo et al. 2016).

Pinus teocote Schltdl. & Cham. (common name: ocote) is an evergreen tree that reaches 10–20 m in height, with a canopy 12–14 m wide and a trunk 0.65 m in diameter. The bark is fissured and grayish brown; leaves are 10–15 cm long. The fruits are ovoid cones 3.5–6.5 cm long. Naturally, its foliage tends to be rounded, but in cultivation it can take on different shapes (Farjon et al. 1997).

Liquidambar styraciflua L. (common name: liquidambar) is a medium- to tall-sized tree, 20–35 m but occasionally up to 41 m, with a trunk up to 1 m (and sometimes more than 2 m) in diameter. Leaves are palmate and lobed, 7–19 cm long and broad. It was well known as a medicinal plant by Native Americans.

Data analysis

The values of tensile strength (Ts) and elasticity (E) of the roots recorded were classified into three categories according to root diameter (Dm); this was done for each of the selected species using Sturges' rule. Subsequently, to identify

which of the recorded variables (Ts or E) had the greatest correlation with respect to Dm, a Spearman correlation analysis was carried out. This analysis was performed in the Statistica 13.3 program (TIBCO Software Inc. 2017). To identify the species that best characterize each Dm category, a non-metric multidimensional scaling (NMDS) analysis was performed using Euclidean distance as the similarity matrix. A PERMANOVA was also performed to test differences in species composition between sites. Both analyses were performed using the Vegan package (Oksanen et al. 2019) in R 3.5.3.

Results

A total of 224 roots from 12 tree species were evaluated, corresponding to 12 genera and 11 families. Five species belong to the TSdF, four to the TTS, and three to the OPF. *Piper amalago* L. turned out to be the species with the highest Ts for the TSdF, while *Randia obcordata* S. Watson was the species with the highest Ts for the TTS, and *Pinus teocote* Schltdl. & Cham. for the OPF. On the other hand, for E, the species with the highest values for both the TSdF and OPF were the same: *Piper amalago* L. for the TSdF and *Pinus teocote* Schltdl.

Table 1. Parameters evaluated by species in the Peregrina Canyon, Mexico. LDm = Large diameter; MDm = Medium diameter; SDm = Small diameter.

Taxon	Diameter Min	Diameter Max	Ts	E
TSdF				
Annonaceae Juss.				
Annona globiflora Schltdl. (Aglo)				
SDm	1.50	2.23	31.59	327.13
MDm	2.23	2.97	14.60	127.42
LDm	2.97	3.70	8.30	24.72
Moraceae Gaudich.				
Ficus cotinifolia Kunth (Fcot)				
SDm	2.10	2.97	54.82	240.11
MDm	2.97	3.83	60.60	283.55
LDm	3.83	4.70	42.11	75.12
Piperaceae Giseke				
Piper amalago L. (Pama)				
SDm	2.30	3.70	99.80	640.88
MDm	3.70	5.10	102.40	161.32
LDm	5.10	6.50	83.25	117.62
Rubiaceae Juss.				
Sommera grandis (Bartl. ex DC.) Standl. (Sgra)				
SDm	1.30	2.87	54.96	361.59
MDm	2.87	4.43	36.10	116.22
LDm	4.43	6.00	21.17	44.16
Cupressaceae Gray				
Taxodium mucronatum Ten. (Tmuc)				
SDm	1.50	3.20	72.90	550.32
MDm	3.20	4.90	61.42	116.93

Taxon	Diameter Min	Diameter Max	Ts	E
LDm	4.90	6.60	48.45	101.51
TTS				
Cannabaceae Martinov				
Celtis laevigata Willd. (Clae)				
SDm	2.00	3.30	33.57	223.36
MDm	3.30	4.60	22.83	58.76
LDm	4.60	5.90	21.42	24.81
Rhamnaceae Juss.				
Karwinskia humboldtiana (Schult.) Zucc. (Khum)				
SDm	2.00	3.00	41.23	267.35
MDm	3.00	4.00	22.68	60.88
LDm	4.00	5.00	22.36	41.11
Rubiaceae Juss.				
Randia obcordata S. Watson (Robc)				
SDm	2.00	3.00	45.95	201.39
MDm	3.00	4.00	28.83	75.07
LDm	4.00	5.00	25.48	74.31
Rutaceae Juss.				
Zanthoxylum fagara (L.) Sarg. (Zfag)				
SDm	1.60	2.97	33.63	181.50
MDm	2.97	4.33	45.00	83.75
LDm	4.33	5.70	19.72	17.75
OPF				
Altingiaceae Horan.				
Liquidambar styraciflua L. (Lsty)				
SDm	2.20	3.27	38.41	133.31
MDm	3.27	4.33	14.40	23.64
LDm	4.33	5.40	30.78	38.14
Pinaceae Spreng. ex Rudolphi				
Pinus teocote Schltdl. & Cham. (Pteo)				
SDm	1.40	2.87	51.94	415.84
MDm	2.87	4.33	33.88	114.72
LDm	4.33	5.80	19.42	48.63
Fagaceae Dumort.				
Quercus rysophylla Weath. (Qrys)				
SDm	1.40	2.60	39.05	319.77
MDm	2.60	3.80	28.26	86.12
LDm	3.80	5.00	29.48	58.41

& Cham. for the OPF. However, for the TTS, *Karwinskia humboldtiana* (Schult.) Zucc. turned out to be the species with the highest E recorded (Table 1).

The E was the variable that best correlated with root diameter. This correlation turned out to be negative but significant ($p < 0.05$).

The PERMANOVA test detected significant differences in species composition among all sites (SStotal = 1366000; SSwithin-group = 628500; $F = 3.52$, $P < 0.001$). The sampled plant communities formed separate groups in the NMDS diagram (Stress = 0.11) (Fig. 4). *Piper amalago* L., *Sommera grandis* (Bartl. ex DC.) Standl., and *Taxodium mucronatum* Ten. were the species with the highest

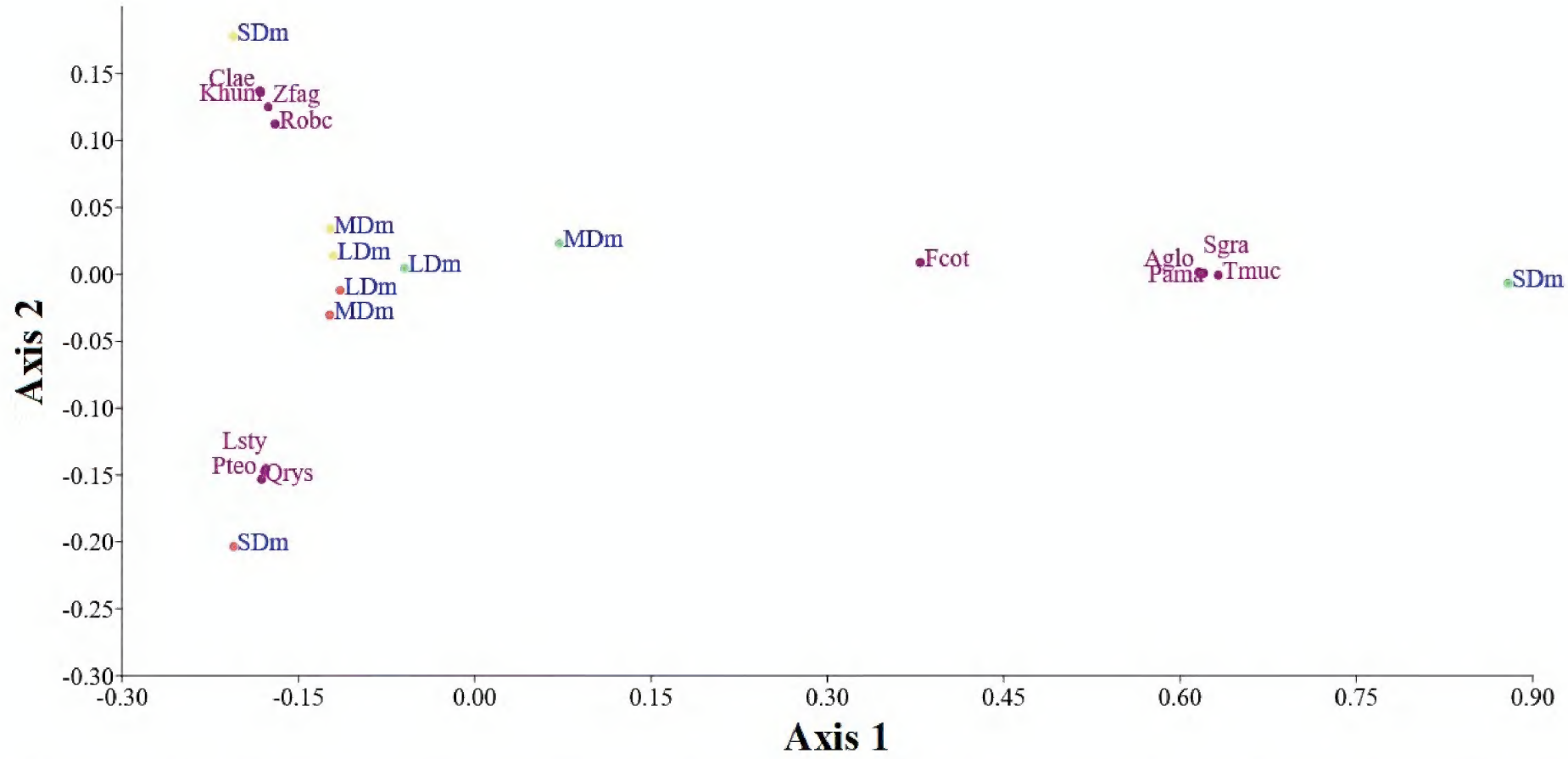

Figure 4. NMDS for plant species elasticity by root diameter categories. TSdF (green), TTS (yellow), and OPF (red). The meaning of the abbreviations is presented in Table 1.

Table 2. Order of maximum values recorded for tensile strength and E of each species.

	Dm	TSdF
Ts	S	*Piper amalago >Taxodium mucronatum > Sommera grandis > Ficus cornifolia > Annona globiflora*
	M	*Piper amalago > Taxodium mucronatum > Ficus cornifolia > Sommera grandis > Annona globiflora*
	L	*Piper amalago > Taxodium mucronatum > Ficus cornifolia > Sommera grandis > Annona globiflora*
E	S	*Piper amalago > Taxodium mucronatum > Sommera grandis > Annona globiflora > Ficus cornifolia*
	M	*Ficus cornifolia > Taxodium mucronatum > Piper amalago > Sommera grandis > Annona globiflora*
	L	*Piper amalago > Taxodium mucronatum > Ficus cornifolia > Sommera grandis > Annona globiflora*
	Dm	**TTS**
Ts	S	*Randia obcordata > Karwinskia humboldtiana > Zanthoxylum fagara > Celtis laevigata*
	M	*Zanthoxylum fagara > Randia obcordata > Celtis laevigata > Karwinskia humboldtiana*
	L	*Randia obcordata > Karwinskia humboldtiana > Celtis laevigata > Zanthoxylum fagara*
E	S	*Karwinskia humboldtiana > Celtis laevigata > Randia obcordata > Zanthoxylum fagara*
	M	*Zanthoxylum fagara > Randia obcordata > Karwinskia humboldtiana > Celtis laevigata*
	L	*Randia obcordata > Karwinskia humboldtiana > Celtis laevigata > Zanthoxylum fagara*
	Dm	**OPF**
Ts	S	*Liquidambar styraciflua > Quercus rysophylla > Pinus teocote*
	M	*Pinus teocote > Quercus rysophylla > Liquidambar styraciflua*
	L	*Liquidambar styraciflua > Quercus rysophylla > Pinus teocote*
E	S	*Pinus teocote > Quercus rysophylla > Liquidambar styraciflua*
	M	*Pinus teocote > Quercus rysophylla > Liquidambar styraciflua*
	L	*Quercus rysophylla > Pinus teocote > > Liquidambar styraciflua*

E and small Dm in the TSdF. On the other hand, *Celtis laevigata* Willd. and *Karwinskia humboldtiana* (Schult.) Zucc. were the species with the highest E and small Dm in the TTS. The species in the OPF with the highest E and small Dm were *Liquidambar styraciflua* L. and *Quercus rysophylla* Weath. (Fig. 4).

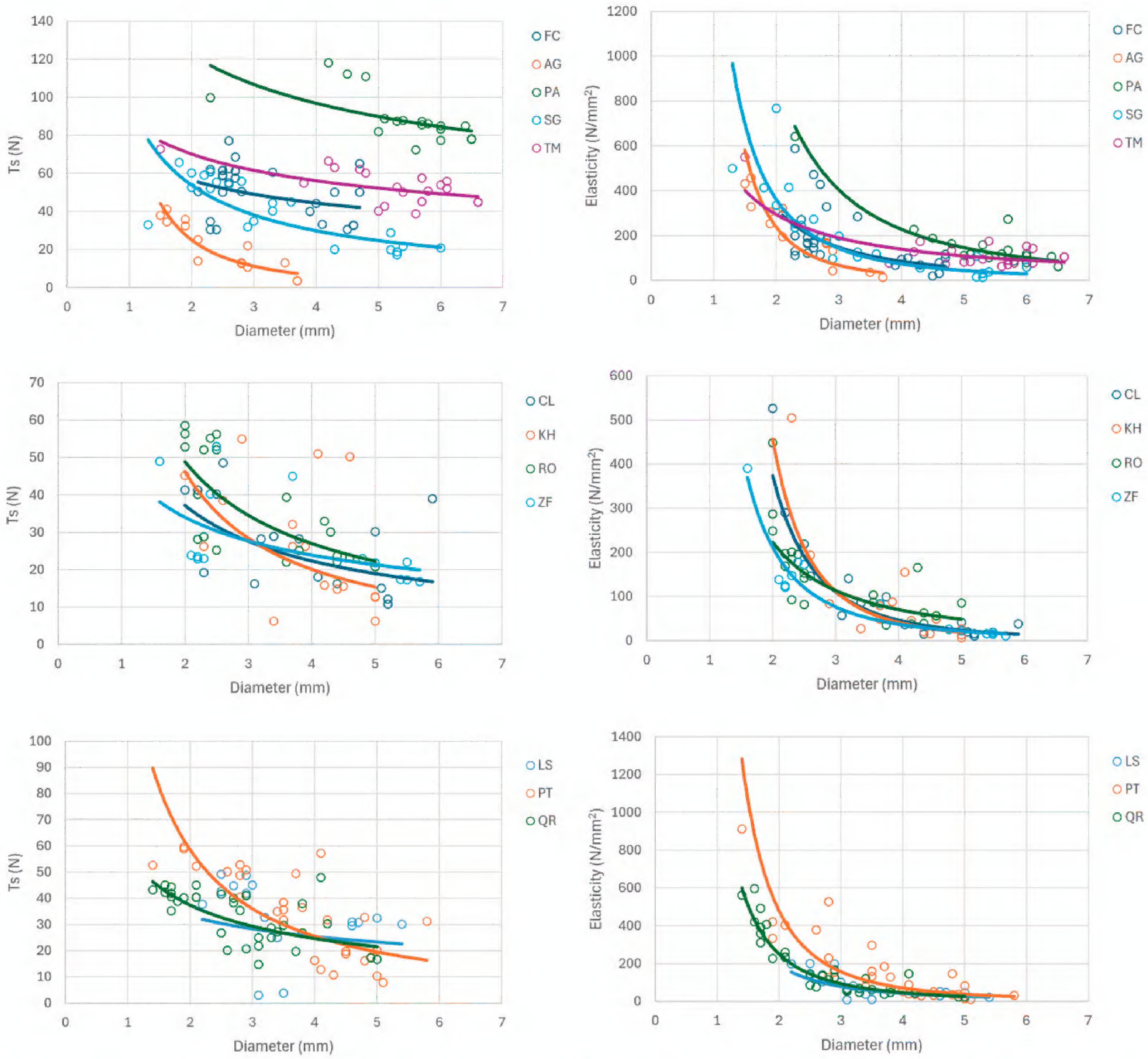

Figure 5. The regression analysis for the three sampling sites fitted a power-law relationship. AG = *Annona globiflora*, FC = *Ficus cotinifolia*, PA = *Piper amalago*, SG = *Sommera grandis*, TM = *Taxodium mucronatum*, CL = *Celtis laevigata*, KH = *Karwinskia humboldtiana*, RO = *Randia obcordata*, ZF = *Zanthoxylum fagara*, LS = *Liquidambar styraciflua*, PT = *Pinus teocote*, QR = *Quercus rysophylla*.

The regression analysis for the three sampling sites fitted a power-law relationship, suggesting that changes in the response variable occur proportionally to a power of the predictor variable rather than in a constant linear pattern (Fig. 5).

The order of maximum to minimum values of tensile strength and elasticity for each species in each diameter category across the three different vegetation types is shown in Table 2. The order shows that *Piper amalago* dominates the maximum values of Ts and E in most diameter categories in the tropical semi-deciduous forest, while in the Tamaulipan thornscrub, *Randia obcordata* and *Karwinskia humboldtiana* alternate among the maximum values. On the other hand, *Liquidambar styraciflua* and *Pinus teocote* share the maximum values across different diameter categories.

Discussion

We investigated the variation of the mechanical properties of thin tree roots, divided into three diameter categories, across three different vegetation communities along an altitudinal gradient. For this study, we used our own classification, statistically partitioning diameters of each species following Sturges' rule. This approach allowed us to account for morphological differences among species and to ensure better comparability, especially in mixed-species datasets (Freschet et al. 2021a; Freschet et al. 2021b). However, the classification of roots remains a complex task because many factors, such as species identity, root morphology, and phenological stage, influence diameter distribution and related properties. In the literature, classification methods vary widely, from personal preferences, fixed-size intervals, and whole-root-system perspectives to more functional or topological approaches (Gu et al. 2017; Liu et al. 2018; Freschet et al. 2021b; Bi et al. 2023). Nevertheless, a careful and standardized classification step is crucial when analyzing diverse vegetation communities, as it strongly influences the interpretation of mechanical properties. Across the tropical semi-deciduous forest (TSdF), Tamaulipan thornscrub (TTS), and oak–pine forest (OPF), thin-root tensile strength (Ts) declined systematically with diameter, while elastic modulus (E) showed clear species- and community-level contrasts. These patterns confirm that properties of thin roots (2–10 mm) are ecologically structured and relevant to shallow landslide initiation zones, and they reveal species that combine high Ts at small diameters with comparatively stiff responses (higher E).

Altitudinal gradients are well known to affect root properties and plant development due to differences in temperature, precipitation, soil pH, nutrients, and minerals, which vary with altitude, thereby modifying the soil environment. Thus, the assessment of plant species' root systems represents a fundamental trait for understanding the contribution of vegetation to reducing shallow landslide instabilities at different altitudes. The measurements of those properties present wide variability in the literature and are affected by uncertainties due to measurement methods and natural variation among plant species. Although studies of root mechanical properties of different species along altitudinal gradients are scarce, some highlight interesting results. Qi et al. (2025) found that species at lower elevations show advantageous morphological characteristics, while roots at higher elevations show greater tensile strength, which can result in more resistant roots. By contrast, Weemstra et al. (2020) found that variation in root properties depends more on small-scale heterogeneity than on large-scale environmental variation. However, in our study, the results for thin roots did not show any trend across the altitudinal gradient. This is consistent with the difference in species composition among vegetation communities and with the notion that species identity and local heterogeneity can override broad elevational signals. Importantly, besides tensile strength (Ts), our measurements of elastic modulus (E) also varied among species and communities, highlighting that both Ts and E are needed to characterize reinforcement potential.

The climate and environment of mountainous regions are unique. Elevation can change temperature and humidity, affecting soil organisms and the presence and performance of vegetation species. Plant species richness, growth, and vegetation type are influenced by climatic limitations. For example, it is well known that the number of tree, shrub, and understory species is reduced as elevation increas-

es (Klimek et al. 2020; Staszel et al. 2022). Furthermore, the growth, morphology, and biomass of thin roots tend to decrease at higher elevations (Finér et al. 2011; Kotas et al. 2018; Sierra-Cornejo et al. 2020). Those changes in root structure have direct implications for their mechanical properties. Reports from other regions suggest that higher elevations often promote the development of finer roots with increased tensile strength, enhancing their ability to resist breakage under soil movement and contributing more effectively to soil reinforcement. Elasticity, on the other hand, determines how much roots can stretch without breaking. The balance between tensile strength and elasticity is therefore crucial for understanding root contributions to slope stability along altitudinal gradients, as roots must be strong enough to anchor soil yet flexible enough to adapt to ground movement. Our findings of community-specific Ts and E, but no consistent elevational trend for thin roots, indicate that species turnover and local site conditions may shape this balance more strongly than elevation alone at the spatial scale of our study.

The relationship between root diameter and tensile strength is well established: thinner roots often exhibit higher tensile strength due to greater cellulose concentration per cross-sectional area, following a negative power-law relationship (De Baets et al. 2008; Meijer 2024). However, in mixed-species environments, species-specific morphology and adaptive strategies can obscure these general trends. Consistent with this expectation, our data did not reveal a consistent tensile strength pattern across diameter classes along the altitudinal gradient, suggesting that species turnover and functional trait diversity between vegetation zones may override altitude-driven patterns. Moreover, incorporating E alongside Ts clarifies that stiffness differences among species can alter how load is shared within the soil–root composite during shear, even when Ts is similar. Overall, the species-resolved Ts–Dm and E–Dm relationships presented here are directly usable for parameterizing root-reinforcement formulations and for identifying candidate species within each vegetation community, while acknowledging that local architecture (density, orientation) and site conditions will govern net reinforcement at the slope scale.

Conclusion

Our study demonstrates that the mechanical properties (Ts and E) of thin roots vary significantly among species across three vegetation types along an altitudinal gradient. While species such as *Piper amalago* and *Pinus teocote* consistently exhibited high Ts and E values, the absence of a consistent altitudinal trend suggests that local site conditions and species-specific traits have a stronger influence on root mechanics than elevation alone. Elasticity showed the strongest negative correlation with root diameter, highlighting the importance of fine root characteristics in mechanical performance.

These findings underscore the importance of accounting for species identity and root morphology when assessing root contributions to soil reinforcement and slope stability. Given the variability in mechanical traits across communities, especially in mixed-species systems, a standardized classification of root diameter and function is essential. Understanding these differences is crucial for improving models of vegetation–soil interaction and for designing effective nature-based solutions in erosion-prone or mountainous environments.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

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Data availability

All of the data that support the findings of this study are available in the main text.

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